Development of a SCRF β=0.81 cavity for an 8 GeV Proton Linac at Fermilab

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***Abstract*—A proposed linac at Fermilab requires many types of RF cavities to accelerate protons from 15 MeV to 8.0 GeV. In this paper we discuss the RF design and initial prototyping of a superconducting 1300-MHz β=0.81, 7-cell elliptical cavity, which covers 0.4 to 1.2 GeV. Analyses of the electromagnetic properties and Lorentz force detuning with stiffening rings are presented. The first stage of prototyping consists of single-cell cavities made from two types of high purity niobium, fine grain and large grain. We describe the fabrication, processing, and testing of the single-cell cavities. At low RF field, measurements of Q_0 and surface resistance are made as a function of temperature, and Q_0 is measured as a function of the RF field amplitude at 2°K. The effects of 120°C in situ baking and post-purification are studied for the large grain cavity.**

***Index Terms*—Accelerator cavities, Superconducting cavity resonators, Superconducting materials, Superconducting resonators.**

I. Introduction

IN order to increase the intensity of the NuMI neutrino beam at Fermilab, it has been proposed to build an 8 GeV proton linac that injects a 0.5 – 2.0 MW beam into the Main Injector for further acceleration [1]. The RF cavity design for the linac changes as β increases. The last two sections contain superconducting 1300-MHz multicell elliptical cavities; a new "β=0.81" design for 0.4 – 1.2 GeV, which is the subject of this paper, and the TESLA, β=1, 9-cell cavity [2].

II. Design

The ~48 β=0.81 cavities will use the same Klystron and couplers as the ~288 TESLA cavities. In order to quickly advance the β=0.81 project, we chose to follow well-tested techniques for cavity design. The cell shape is approximately scaled from the SNS β=0.81, 805 MHz, 6-cell elliptical cavity. This was chosen over the low-loss shape because the larger inclination angle at the iris, 7° .vs. 2.5°, reduces the risk of incomplete cleaning. The radius at the iris is increased over the strictly scaled SNS design in order to increase the cell-to-cell coupling to 1.6%, which we believe allows adequate field flatness in a 7-cell structure.

Other design criteria are:

- Maintain Bp/Ep similar to TESLA: 110 mT / 51.6 MV/m = 2.13 mT/MV/m.
- Beam tubes same diameter as TESLA cavities.
- Flanges based on 4-5/8 in. Nb45-Ti Conflat® geometry.

Fig. 1 shows the electric field lines for the π mode in a quarter section of the β=0.81 7-cell cavity. The geometrical parameters of a cell are defined in Fig. 2 and given in Table I for both the mid-cell and end-cell. Table II compares RF parameters at B_p = 110 mT (a reasonable performance goal for the TESLA cavity) for the TESLA cavity, the β=0.81 7-cell cavity, and the β=0.81 single-cell prototype, which has the large diameter beam tube at both ends.

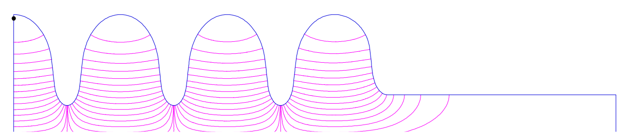

Fig. 1 Electric field lines for the π mode of the β=0.81 7-cell cavity. A quarter section is shown.

An MWS-ANSYS coupled analysis determined the optimal position of a stiffening ring to minimize the frequency shift due to Lorentz forces. With fixed boundary conditions, the detuning coefficient has a minimum value of KL = 0.94 $Hz/(MV/m)^2$ with the ring at a radius of 43 mm. With open boundary conditions, KL = 33 $Hz/(MV/m)^2$.

III. Prototype plans and single-cell fabrication

The planned prototypes include a single-cell cavity, followed by a "simple" 7-cell cavity with symmetric end cells and no power and higher order mode (HOM) couplers, and finally a realistic 7-cell cavity that includes an end-cell for damping HOMs (if required), coupler ports for power and for HOM damping, stiffeners for Lorentz force detuning, and a helium vessel. In this paper we describe the fabrication and testing of single-cell prototypes made with both fine grain and

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large grain niobium.

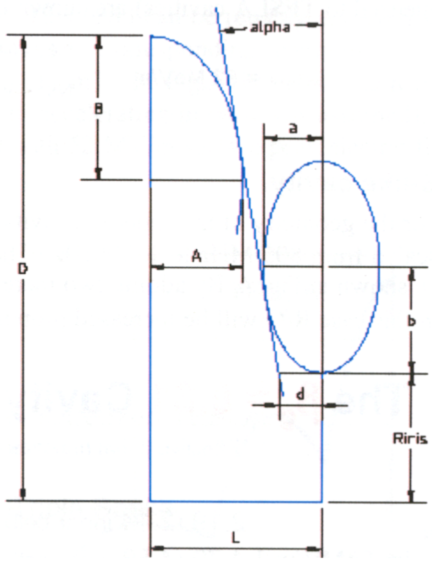

Fig. 2 Parameters defining the cell geometry of the β=0.81 cavitv.

Table I Cell geometry for β=0.81 cavity

Value	units	mid-cell	End-cell & 1-cell prototype
B	cm	4.371	3.167
A	cm	3.362	3.167
a	cm	1.138	1.338
b	cm	2.088	2.341
D	cm	10.3131	10.3131
R(iris)	cm	3.05	3.9
d	cm	0.91	1.081
α	degrees	7	7
L	cm	4.67	4.67

Table II Compare 1300MHz cavities at B_p=110 mT

Quantity	units	TESLA	β=0.81 7-cell	β=0.81 1-cell proto.
β		1	0.81	0.81
α	degrees	13.3	7	7
E_p/E_a	-	2.0	2.19	2.18
B_p/E_a	mT/MV/m	4.26	4.79	5.26
k_{cc}	%	1.8	1.6	-
(R/Q)/cell	Ω	115	79.1	62.3
G	Ω	270	227	229
B_p	mT	110	110	110
E_a	MV/m	25.8	23.4	20.9
E_p	MV/m	51.6	51.1	45.6

A. Niobium material for the single-cell prototypes

Jlab supplied both the fine grain and large grain material from stock that was successfully used in previous tests. The fine grain niobium has the TESLA thickness of 2.8 mm and meets the TESLA specifications for high RRR niobium.

The large grain material was cut from an ingot ("ingot D") supplied by CBMM [3]. It has RRR ~ 280 and a tantalum content of ~800 ppm, somewhat higher than the TESLA specification. The large grain disks used to form the half-cells were cut from the ingot using wire EDM. Due to the EDM, the large grain cavities must undergo hydrogen degassing.

The EDM left striations on the surface that were partially smoothed using Scotchbrite prior to deep drawing. After a large grain half-cell was fabricated (including the beam tube and flange), the interior surface received further polishing. It was mounted on a lathe and rotated while being polished with progressively finer aluminum oxide abrasives, ending with a 20 µm Emory cloth. More polishing was required at the grain boundaries. After the polishing was complete (~1/2 hour per half-cell), a light BCP etch was performed, and the surface, including the grain boundaries, was smooth.

B. Single-cell fabrication by MSU

Two fine grain and two large grain single-cell cavities were fabricated by MSU. The NbTi flanges were machined and electron-beam (e-beam) welded to the Nb beam tubes. Fine grain and large grain disks, shown in Fig. 3, were deep drawn and coined to produce the half-cells also shown in Fig. 3. Fig. 4 shows the deep draw and coining dies along with some copper test parts. The length of the equator weld-prep was adjusted to give 1300 MHz. Fig. 5 shows the set up for the e-beam weld that joins the half-cell to the beam tube at the iris. A full-penetration e-beam weld at the equator completed the single-cell cavity.

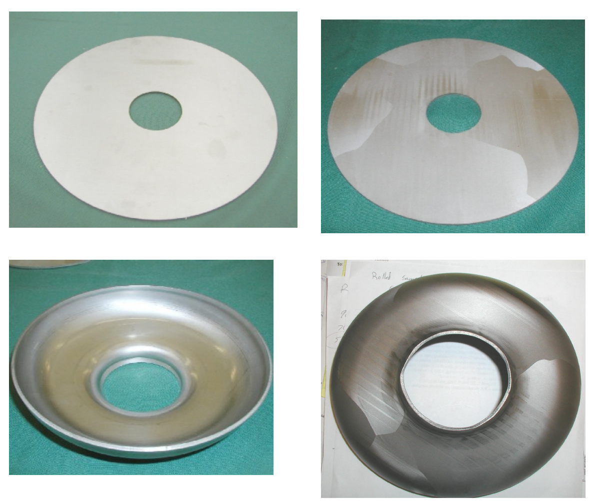

Fig. 3 Nb disks (top) and stamped half cells (bottom) for the fine grain (left) and large grain (right) material.

IV. PROCESSING AND RF TESTS WITH THE SINGLE-CELLS

A. Fine grain cavities at MSU

The cavity interior was etched 180 μm using BCP 1:1:2 at 14°C, followed by a rinse with ultra pure water. Following a high-pressure rinse, the cavity dried in a class 20 portion of the clean room [4]. In preparation for RF tests in a vertical dewar, flanges for vacuum and for the power and pickup antennae were assembled in the clean room. Fig. 6 shows a cavity in position for the closed loop BCP, high pressure rinse, and flange attachment. In order to minimize Q_0 reduction due to hydrides forming from dissolved hydrogen between 150°K and 60°K, the 200-liter dewar was cooled down rapidly to 4.4°K.

Fig. 4 Half-cell forming dies with copper test parts.

The initial RF testing of one cavity is reported here in detail. When initially raising the field at 2°K, there was some RF conditioning. Helium processing was used to eliminate field emission that started at E_p ~ 20 MV/m. After this, thermal breakdown occurred at E_p = 38 MV/m (B_p = 90 mT, E_a = 17 MV/m). Fig. 7 shows Q_0 (at low field) as a function of temperature from 4.4°K to 1.5°K, and Q_0 as a function of E_p at 2°K. The measurement Q_0(1.5°K) ~ 3 x 10^{10} corresponds to a surface resistance of ~8 nΩ and a residual resistance of ~7 nΩ.

Fig. 5 Sciaky's electron beam welder in position to join the half-cell to the beam tube

Additional tests with this and a second fine grain cavity yielded similar results, with thermal breakdown occurring between E_p = 35 and 40 MV/m (Bp = 83 – 95 mT). A 120°C "in situ" bake for 12 hours with the second cavity slightly improved the BCS Q but did not increase the maximum field.

Fig. 6 Processing a fine grain single-cell cavity at MSU: Closed loop BCP (upper left). High pressure rinse in the clean room (lower left). Attaching flanges for vacuum and the power and pickup antennae for RF tests in the 200 liter vertical dewar (right).

B. Large grain cavities at Jlab

For two large grain cavities, "Single-cell 1/2" and "Single-cell 3/4", RF tests were made after four sequential treatments:

1. ~50 μm was removed by BCP 1:1:1 at room temperature prior to H degassing at 600°C for 10 hours. Another 50 μm was removed by BCP 1:1:1, and the cavity was high pressure rinsed for 1 hour, dried in a class 10 clean room for 2 hours, installed in a vertical dewar and evacuated to < 1 x 10^{-8} mbar before starting Test #1.
2. Prior to Test #2 the cavity was baked "in situ" at 120°C for 12 hours.
3. Prior to Test #3 the cavity was post-purified in a titanium box at 1250°C for 3 hours. An additional 50 μm was removed by BCP 1:1:1, followed by a high-pressure rinse and evacuation.
4. Prior to Test #4 the cavity was baked in situ at 120°C for 12 hours.

The RF tests consisted of measuring the dependence of surface resistance with temperature between 4.2°K and 2°K and measuring Q_0 .vs. E_{acc} at 2°K. The residual resistance (R_{res}) is extracted from the temperature scan using BCS theory.

Fig. 8 and Fig. 9 show the Q_0 .vs. E_{acc} scan for the four tests of Single-cell 1/2 and Single-cell 3/4 , respectively.

Some multipacting was observed that quickly processed. During Test #2 for single-cell 1/2, field emission suddenly started at E_{acc} = 24 MV/m and did not process away.

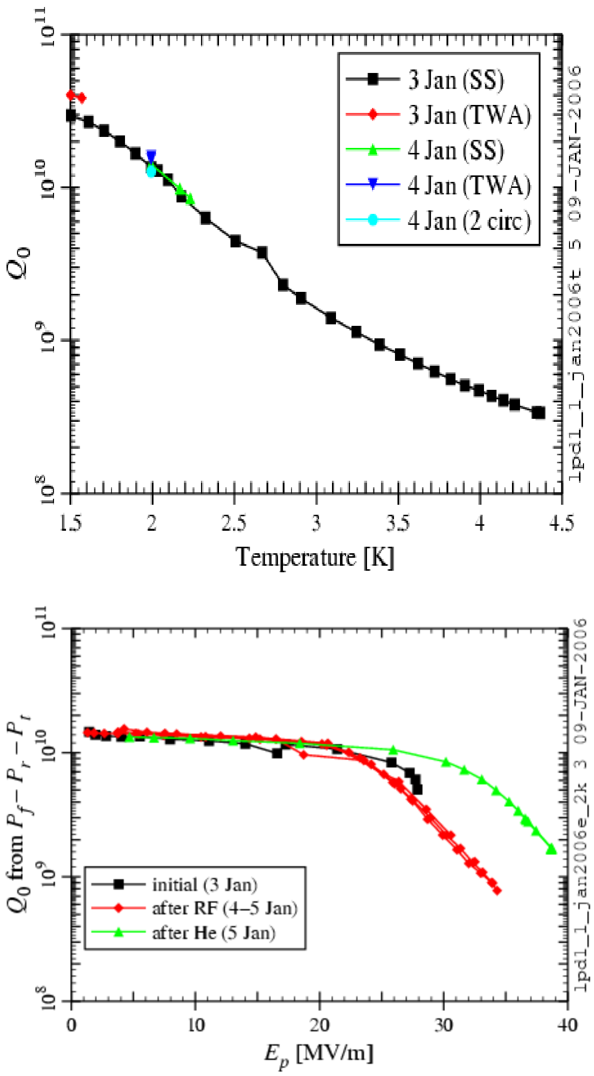

Fig. 7 Tests with a fine grain cavity. Q_0 (at low field) as a function of temperature (top) and Q_0 as a function of E_p at 2K (bottom).

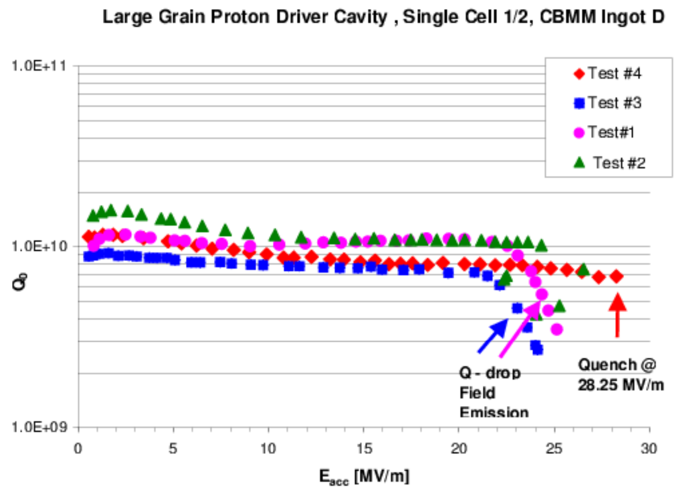

Fig. 8 Q_0 versus E_{acc} tests of the large grain cavity Single-cell 1/2. The tests are defined in the text.

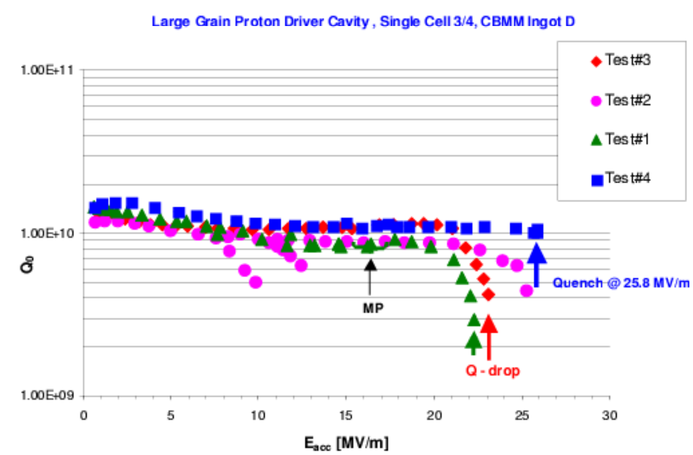

Fig. 9 Q_0 versus E_{acc} tests of the large grain cavity Single-cell 3/4. The test are defined in the text.

The Q drop at high field was always reduced by the in situ baking. Table III gives R_{res}, B_{peak}(max), E_{acc}(max), and Q_0(at B_{peak} = 110 mT). While the highest fields before quenching were achieved in Test #4, values for the fairly standard processing of Test #2, B_{peak}(max) = 139 mT and 133 mT, comfortably exceed the "performance goal" of 110 mT. A similar value of B_{peak}(max) = 127 mT (E_{acc}(max) = 31.2 MV/m) was achieved in Test #2 using a TESLA shaped large grain cavity made from the same ingot.

Table III Testing two large grain cavities at Jlab

	R_{res} [nΩ]	B_p(max) [mT]	E_a(max) [MV/m]	Q_0(110 mT, 20.9 MV/m)
Cavity 1/2				
Test #1	10.3±1.5	132	25.1	1.0E+10
Test #2	8.6±0.8	139	26.5	1.0E+10
Test #3	13.4±1.6	127	24.1	7.0E+09
Test #4	14.1±1.1	148	28.3	8.0E+09
Cavity 3/4				
Test #1	N/A	117	22.3	6.5E+09
Test #2	13.7±0.9	133	25.3	8.5E+09
Test #3	14.2±1.3	121	23.1	1.0E+10
Test #4	7.7±0.6	136	25.8	1.0E+10

V. Summary and Plans

We described the design of a 1300 MHz, 7-cell, elliptical cavity for operation at $\beta = 0.81$ in a proposed 8 GeV proton linac at Fermilab. The cell shape is close to a scaled 805 MHz, β=0.81 SNS cavity. Two fine grain and two large grain niobium single-cell prototype cavities were fabricated. The large grain material was cut directly from an ingot and the subsequent surface polishing was described.

The results of cryogenic RF tests for two fine grain and two large grain single-cell cavities were presented. After similar processing (BCP, 120°C in situ baking), the fine grain cavities reached peak surface fields of B_p = 83 - 95 mT, and the large grain cavities reached higher values of B_p = 133 - 139 mT.

The material for two “simple” 7-cell cavities, one fine grain and one large grain, is in house, and fabrication is planned to begin soon.

References

[1] Proton Driver Technical Design Study Document, http://protondriver.fnal.gov/#Technical_Design_Link

[2] TESLA Technical Design Report, http://tesla.desy.de/new_pages/TDR_CD/start.html

[3] CBMM, Brazil, http://www.us.cbmm.com.br/index.htm

[4] T. Grimm, et al, “Superconducting RF Activities at NSCL”, presented at SRF2001.